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EQUATIONS AND FORTRAN PROGRAM FOR APPROXIMATE AERODYNAMIC HEAT TRANSFER AND TRANSIENT TEMPERATURE DISTRIBUTIONS FOR LEADING EDGES AND FLAT PLATE SURFACES

by

L. H. Johnson

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October 1965

U S ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA

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Aerodynamics Branch
Advanced Systems Laboratory
Research and Development Directorate
U. S. Army Missile Command
Redstone Arsenal, Alabama 35809

ABSTRACT

The equations and a Fortran program to calculate supersonic and hypersonic aerodynamic heat transfer rates and transient temperature distributions for spherical leading edges and flat plate surfaces are presented in this report. The missile skin is composed of one to three different slab materials and/or thin wall combinations for flight trajectories or wind tunnel conditions. The Fortran program is written for the IBM 1620 40K digital computer.

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Appendix A

FORTRAN PROGRAM AND ITS USAGE

ILLUSTRATIONS

1. Introduction

A general purpose Transient Temperature Aerodynamic Heat Transfer IBM 1620 Digital Computer Program for supersonic and hypersonic flight speeds is described herein. This computer program considers spherically blunted leading edges and/or flat plate surfaces. One dimensional temperature distributions through a missile skin composed of one to three different slab materials or a thin wall material followed or preceded by one or two different slab materials is available. The required flight environment is either a trajectory input based on the ARDC 1959 atmosphere or constant altitude and local flow properties (wind tunnel conditions).

2. Analysis

a. Stagnation Regions

Aerodynamic heat transfer coefficients for spherically blunted leading edge surfaces are separated into two regions. For nondissociated gas properties, corresponding to flight speeds up to 6000 ft/sec, the external aerodynamic heat transfer coefficients for laminar and turbulent boundary layers are developed in this report. For dissociated gas properties, an approximation to the exact stagnation point heat transfer rate solution of Fay and Riddell[1] and Detra and Hidalgo[2] is used.

(1) Nondissociated Aerodynamic Heat Transfer Coefficient. The important variables affecting the aerodynamic heat transfer coefficient for a spherically blunted leading edge surface are shown in Figure 1.

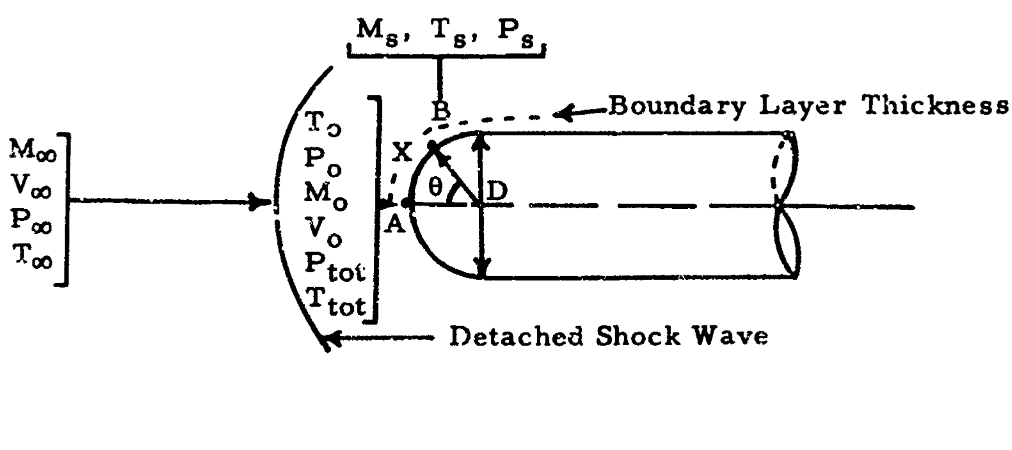

Figure 1. Important Variables Affecting the Aerodynamic Heat Transfer Coefficient for a Spherically Blunted Leading Edge Surface

(a) Laminar Boundary Layer. A modified Reynolds analogy for flow with constant thermal and transport properties through the boundary layer for spherical and cylindrical surfaces is used.

$$St_s = \frac{Nu_{inc}}{Re_s\ Pr_s} = \frac{C_f}{2}\ Pr_s^{-0.6} \tag{1}$$

$$\frac{H_{inc}\ Y}{k_s} = \frac{C_f}{2}\ Re_s\ Pr_s^{\ 0.4}\ . \tag{2}$$

Measurements of local skin friction coefficients on spherical and cylindrical surfaces indicate the normal laminar flow correlation for zero pressure gradient flow may be applied provided the constant of proportionality, using local Reynold's number, is considered to vary with location along the surface:

$$C_f = \frac{f_1}{\sqrt{Re_s}}\ . \tag{3}$$

The factor f_1 of Equation (3) varies from 1.526 at the stagnation point to approximately 0.664 at a position 90 degrees from the stagnation point for the sphere and from 1.14 to 0.664 for the cylinder. Equation (2) can be expanded to

$$H_{inc}\ Y = \frac{f_1}{2} k_s \left[\frac{\rho_s V_s Y}{\mu_s}\right]^{0.5} Pr_s^{\ 0.4}\ . \tag{4}$$

Since the stagnation point value of Y and V_s are zero and large errors of heat transfer coefficient result from Equation (4) in the areas close to the stagnation point, it becomes convenient and more accurate to define a term β as given by Equation (5):

$$V_s = \beta Y\ . \tag{5}$$

The value of β varies along the surface, with the sphere diameter, and with the free stream Mach number and temperature. At the stagnation point, application of elementary calculus yields the nondimensional velocity gradient $\left(\frac{dV}{dY}\right)_0$. This nondimensional velocity gradient is a function of free stream Mach number only. A ratio of β/β_0 was found to depend only on the location on the spherical surface.

Substituting βY for V_s and $\frac{P_s}{R_g T_s}$ for ρ_s in Equation (4) yields

$$H_{inc} \cdot Y = \frac{f_1}{2} \; k_s \left[\frac{P_s \beta Y^2}{R_g T_s \mu_s} \right]^{0.5} Pr_s^{0.4} \qquad (6)$$

By dividing Equation (6) by Y, multiplying by $\sqrt{D}$, then multiplying the right hand side by $\sqrt{\beta_0/\beta_0}$ and $\sqrt{V\infty/V\infty}$, the equation may be written:

$$H_{inc} \cdot \sqrt{D} = 0.5 \left[\frac{V_\infty P_s}{R_g} \right]^{0.5} Z_1 \, Z_2 \, Z_{3\,s} \;, \qquad (7)$$

where

$$Z_1 = \sqrt{\frac{\beta_0 D}{V_\infty}} = \left\{ \left[1.4 + \frac{7}{M_\infty^2} \right] \left[0.139 \left(7 - \frac{1}{M_\infty^2} \right) \right]^{2.5} \right\}^{0.25} , \qquad (8)$$

$$Z_2 = f_1 \sqrt{\beta/\beta_0} = f(\theta) \qquad (9)$$

and

$$Z_3 = kP_r^{\;0.4} / \sqrt{T\mu} \;. \qquad (10)$$

Equation (7) has been developed for constant thermal and transport properties with Z_3 evaluated at local conditions. For an appreciable variation of temperature within the boundary layer, a reference temperature[3] (T^*) has proven to give excellent aerodynamic heat transfer coefficients:

$$T^* = T_s \left[0.50 + 0.039 \, M_s^2 \right] + 0.50 \, T_W \;. \qquad (11)$$

The properties of Z_3 in Equation (10) required to be evaluated at T^*, are indicated by the asterisk superscript (*), and are defined by the following equations:

When $T^* < 1000°R$

$$k^* = \frac{0.23791763 \times 10^{-6}\, T^{*\,1.52}}{T^* + 198.6}. \qquad (12a)$$

When $T^* \geq 1000°R$

$$k^* = 11.997\mu^*, \qquad (12b)$$

Where

$$\mu^* = \frac{0.249 \times 10^{-6}\, T^{*\,0.63}}{g_a} \qquad (13)$$

$$p_r^* = \mu^* c_p^* g_a / k^* \qquad (14)$$

and $C_p^* = f(T^*)$, as defined by Equation (56).

Then

$$H\sqrt{D} = 0.5 \left[\frac{V_\infty P_g}{R_g}\right]^{0.5} Z_1 Z_2 Z_3^* . \qquad (15)$$

Figures 2 and 3 present Z_1 and Z_2.

At the stagnation point, the reference temperature becomes

$$T_o^* = 0.5 \left[T_{TOT} + T_w\right] \text{ for } M_{\infty_0} \longrightarrow 0.0\,, \qquad (16)$$

where the total temperature, T_{TOT}, at the stagnation point is the total temperature of the free stream.

(b) Turbulent Boundary Layer. It is possible to have turbulent boundary layer flow over some portion of the leading edge and a method for the aerodynamic heat transfer coefficient is presented. The basic development is similar to the laminar boundary layer heat transfer development.

$$St_g = \frac{C_f}{2} P_{r_g}^{-2/3} \qquad (17)$$

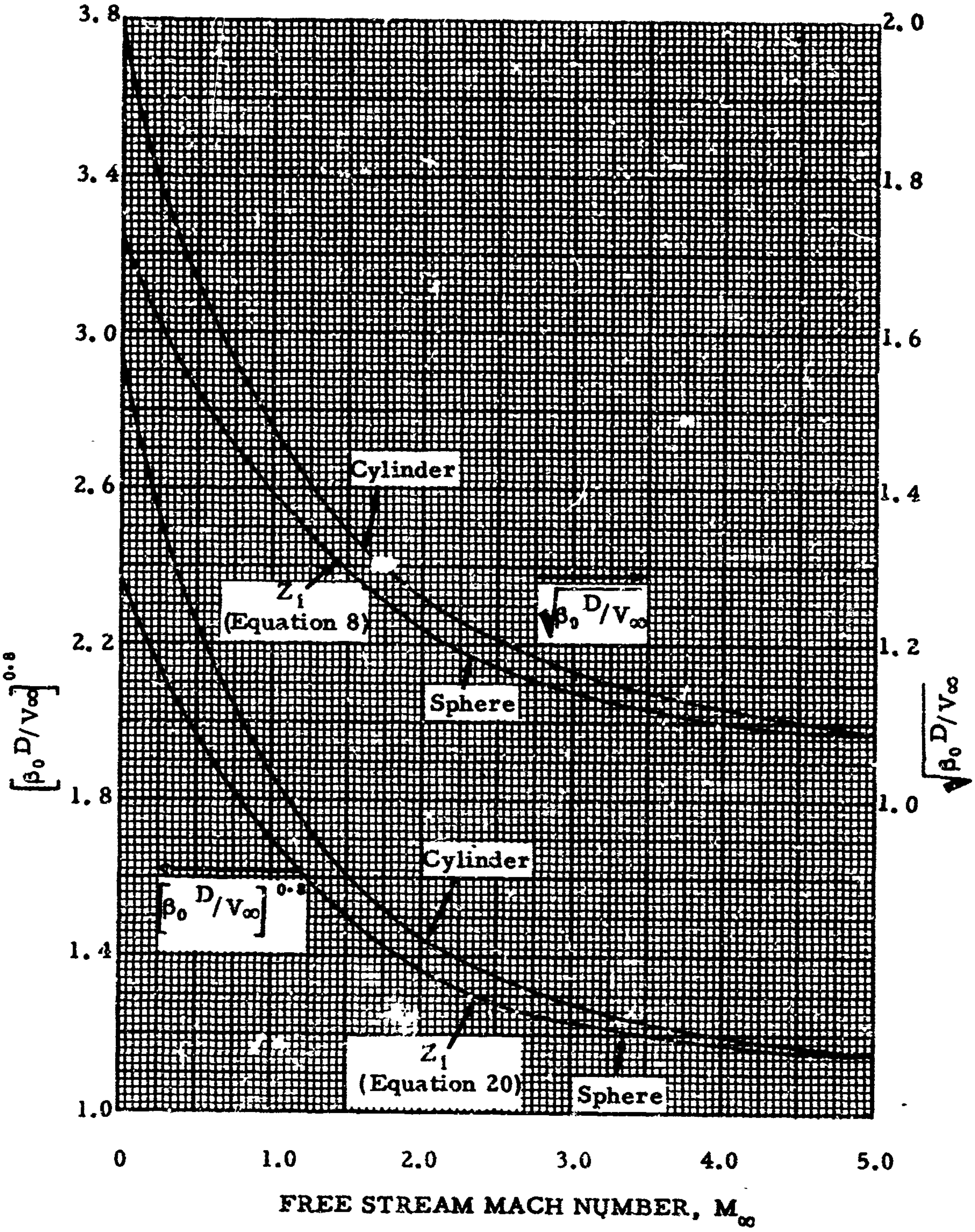

Figure 2. Stagnation Point Velocity Gradient

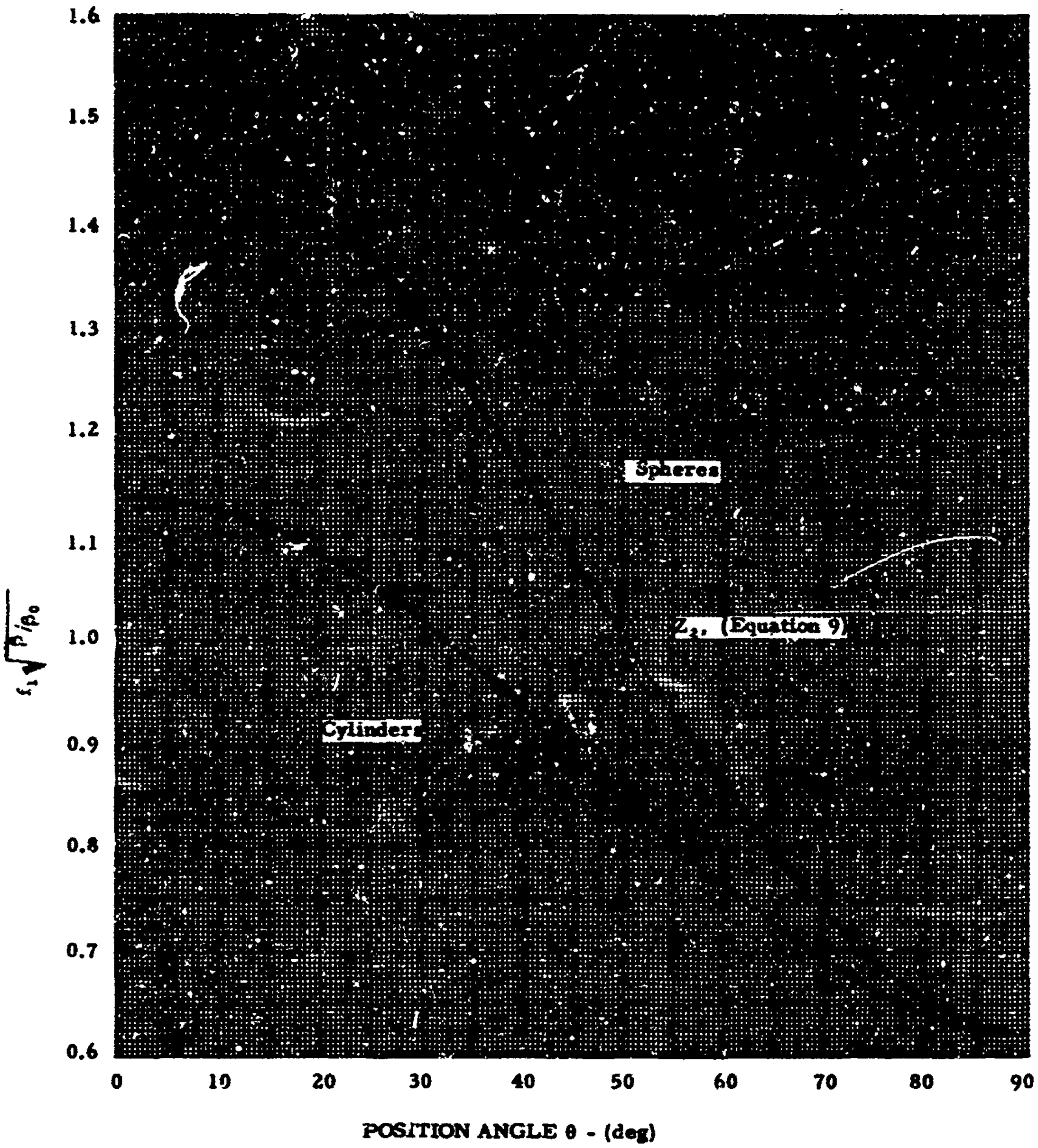

Figure 3. Laminar Leading Edge Skin Friction Proportionality and Velocity Gradient

The skin friction coefficient for turbulent boundary layers on the leading edge can be expressed as

$$C_f = \frac{f_2}{Re_s^{0.2}} \quad . \tag{18}$$

The leading edge geometry has only a minor effect on the value of the proportionality constant f_2 as compared to the laminar boundary layer. The final equation for turbulent leading edge aerodynamic heat transfer coefficient is

$$HD^{0.2} = 0.5\left[\frac{V_\infty P_s}{R_g}\right]^{0.8}\left(\frac{Y}{D}\right)^{0.6} Z_1 Z_2 Z_3^{*} , \tag{19}$$

where

$$Z_1 = \left[\frac{\beta_o D}{V_\infty}\right]^{0.8} \tag{20}$$

$$Z_2 = f_2\left(\frac{\beta}{\beta_o}\right)^{0.8} \tag{21}$$

and

$$Z_3 = \frac{k^* \, Pr^{*\,1/3}}{(T^* \mu^*)^{0.8}} \quad . \tag{22}$$

The exponents of Equation (14) reflect the basic changes in the skin friction correlation. Figures 2 and 4 show variations of Z_1 and Z_2 . The term $(Y/D)^{0.6}$ will cause a maximum aerodynamic heat transfer coefficient away from the stagnation point on a given surface and theoretically a value of zero at the stagnation point. In reality, the stagnation point flow is laminar and thus the aerodynamic heat transfer coefficient will not become zero. This turbulent analysis is not included in the Fortran program.

(c) Approximate Pressure Distribution. The reference temperature , T^*, requires the local Mach number and local temperature. The basic aerodynamic heat transfer equations, Equation (7) for laminar boundary layer and Equation (19) for turbulent boundary

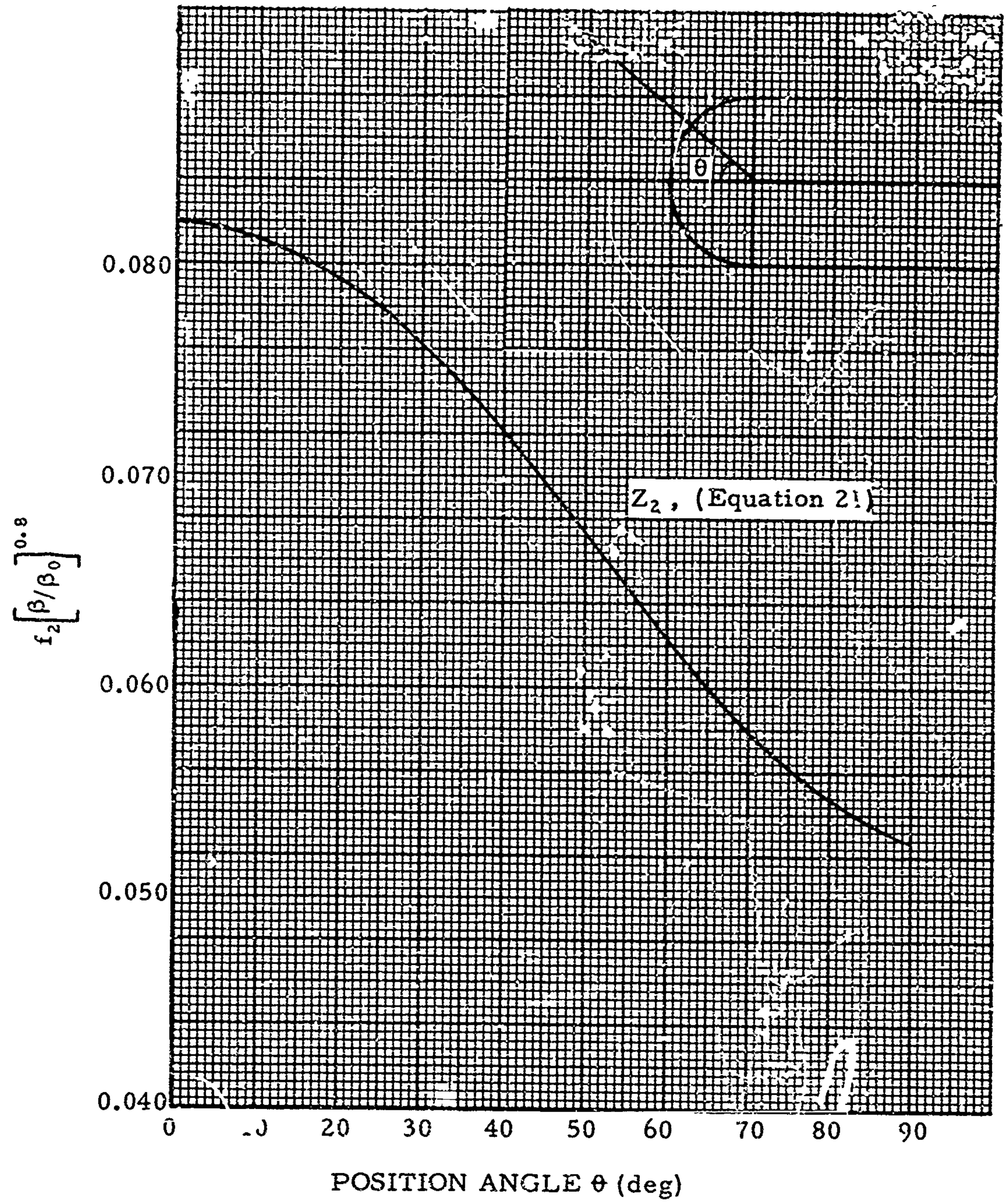

Figure 4. Turbulent Leading Edge Skin Friction Proportionality and Velocity Gradient

layers , require local pressure value. A modified Newtonian-Prandtl-Meyer pressure ratio, P_s, as a function of angular position, θ is used.

$$P_s = P_\infty \frac{P_s}{P_{TOT}} \frac{P_{TOT}}{P_\infty} , \tag{23}$$

where

$$\frac{P_s}{P_{TOT}} = 1 - 0.957 \sin^2 \theta . \tag{24}$$

The local Mach number is determined from the following equations:

$$M_s^{\,2} = \left(\frac{2}{\gamma - 1}\right)\left[\left(\frac{P_s}{P_{TOT}}\right)^{-\frac{\gamma - 1}{\gamma}} - 1\right] \tag{25}$$

and

$$\frac{P_{TOT}}{P_\infty} = \left\{\left[\frac{(\gamma + 1)\, M_\infty^{\,2}}{2}\right]^{\gamma} \left[\frac{\gamma + 1}{2\,\gamma M_\infty^{\,2} - (\gamma - 1)}\right]\right\}^{\frac{1}{\gamma - 1}} . \tag{26}$$

The local temperature T_s is obtained from:

$$\frac{T_s}{T_\infty} = \left[\frac{2 + (\gamma - 1)\, M_\infty^{\,2}}{2 + (\gamma - 1)\, M_s^{\,2}}\right] \tag{27}$$

for surface positions away from the stagnation point. At the stagnation point, the reference temperature, T^*, of Equation (11) does not require local temperature.

(2) Dissociated Air Aerodynamic Heat Transfer Rates. An approximate equation for the exact stagnation point aerodynamic heat transfer rate for flight velocities greater than 6000 ft/sec is presented.[2]

$$Q_w \sqrt{R_n} = 865 \left(\frac{V_\infty}{10^4}\right)^{3.15} \sqrt{\frac{\rho_\infty}{\rho_{sea\ level}}} \left[\frac{h_0 - h_w}{h_0 - h_{w_{300}}}\right] \tag{28}$$

where

$$h_o = \text{stagnation enthalpy} = 6006\ T_\infty + 0.5\ V_\infty^2 \qquad (28a)$$

$$h_w = \text{enthalpy at } T_w,\ ^\circ R = 778\ g_a\ c_p\ T_w \qquad (28b)$$

and

$$h_{w_{300}} = \text{enthalpy at } 300,\ ^\circ k = 3244100. \qquad (28c)$$

For variation of laminar heat transfer rates around the spherical blunted leading edge, the Lee's ratio of heat transfer rate to stagnation point heat transfer rate[3] QR is presented in Figure 5.

Turbulent leading-edge boundary layer heat-transfer rate analyses are not included for the hypersonic flight speeds.

b. Flat Plate Regions

The aerodynamic heat-transfer coefficients for laminar and turbulent boundary layers over a flat plate and/or cone surface were developed in detail.[4] Aerodynamic heat transfer variables are illustrated in Figure 6.

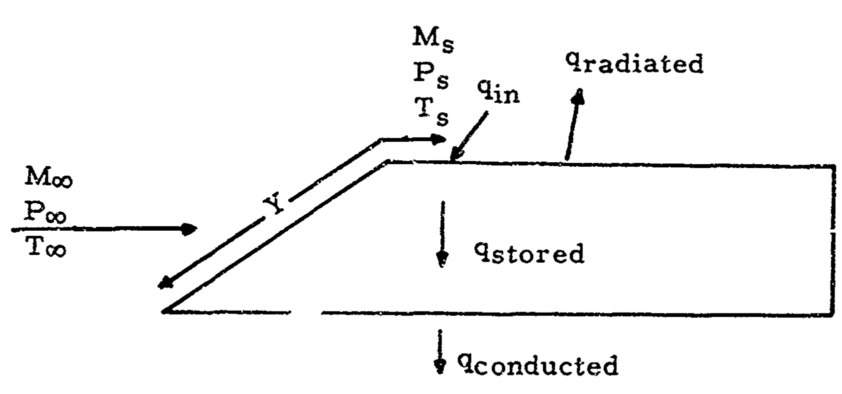

Figure 6. Aerodynamic Heat Transfer Variables for Flat Plates or Cones

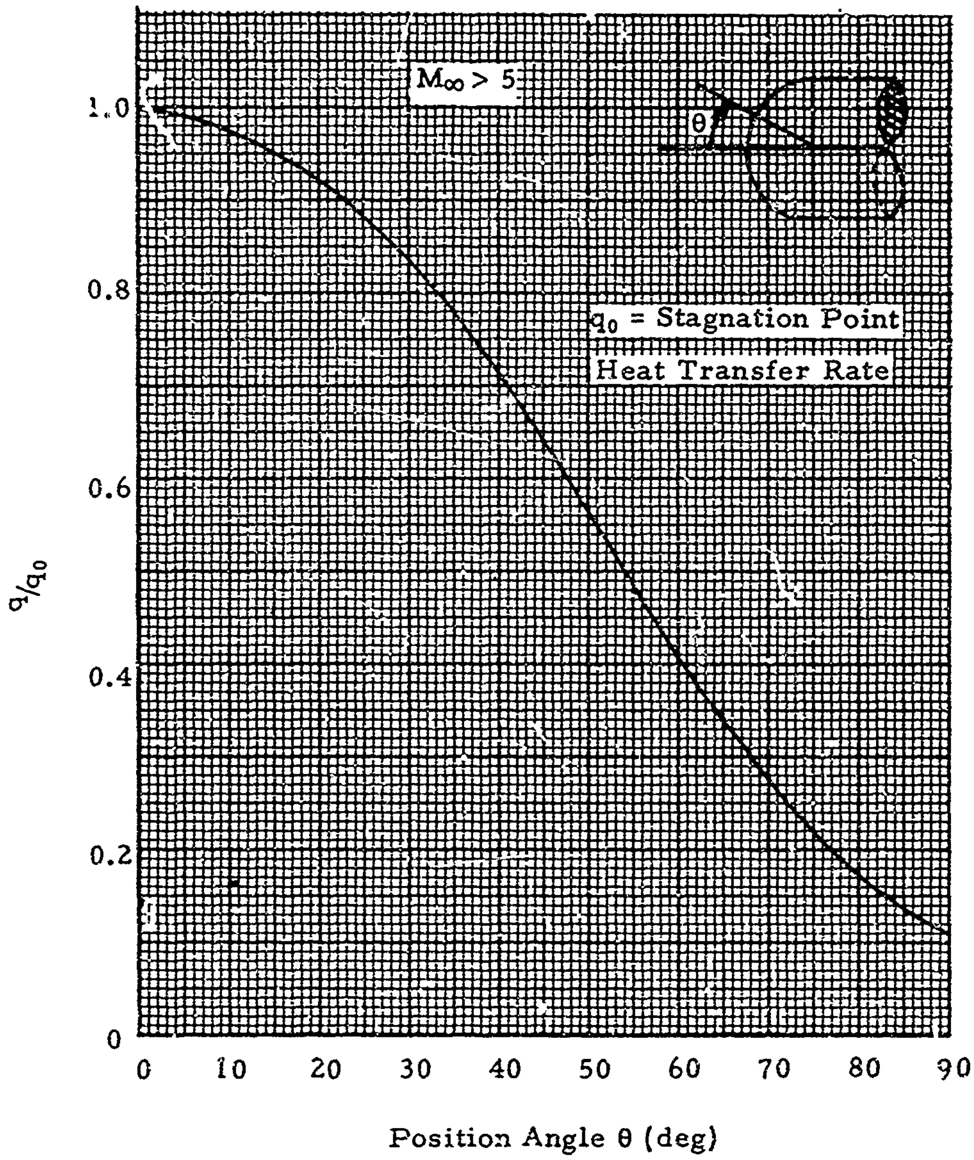

Figure 5. Laminar Heat Transfer Distribution

The following equations express the flat plate aerodynamic heat-transfer coefficients:

$$H_{FP} = C \cdot g_a \left[\sqrt{\frac{T_s \gamma_s}{R_g}} \; \frac{P_s M_s}{T^*} \right]^n \left[\frac{\mu^*}{Y} \right]^{1-n} \frac{Cp_s}{P_r{*}^{2/3}} \cdot \qquad (29)$$

For laminar boundary layers

$$C = 0.332 \qquad (30)$$

$$n = 0.50\ , \qquad (31)$$

and for cone surfaces

$$H_{cone} = H_{FP} \cdot \sqrt{3}\ . \qquad (32)$$

For turbulent boundary layers

$$C = 0.01396 \qquad (33)$$

$$n = 0.85\ , \qquad (34)$$

and for cone surfaces

$$H_{cone} = H_{FP} \cdot \frac{2}{\sqrt{3}} \cdot \qquad (35)$$

Also, the Reynolds number may be defined

$$Re = 1063446\ P_s M_s\ Y \sqrt{\gamma}_s\ (T_s + 198.6)/T_s^2\ , \qquad (36)$$

where γ_s is defined by Equation (57).

c. Time Increment and Material Properties

The time increment, Δt, is critical to the finite difference solution for the temperatures. The following properties are given for each material; density, ρ ; specific heat, C_p; thermal conductivity, k; total thickness, τ_{tot}; and number of layers, NLAY.

$$\tau = \tau_{tot}/NLAY \qquad (37)$$

$$\Delta t = \frac{0.5\rho C_p \tau^2}{k + V_1 \tau} \quad , \qquad (38)$$

where $V_1 = 10$ for first material, estimate for maximum value, and $V_1 = 0$ for following materials. The time increment should be approximately the same for all the materials used.

Equation (38) is solved for each material and the smallest value is used.

Other required material functions are:

$$F_1 = \Delta t/(\rho \ C_p \ \tau)_1 \qquad (39)$$

$$F_{2,3..} = \left(\frac{k}{\tau}\right)_m \cdot \left(\frac{\tau}{k}\right)_{m-1} \qquad (40)$$

and

$$B_m = \Delta t \left(\frac{k}{\rho C_p \tau^2}\right)_m \quad , \qquad (41)$$

where m is the number of the material.

d. <u>One Dimensional Temperature Distribution</u>

The basic heat balance for a multi-material skin is developed below.

NL = Total number of layers for all materials plus end point (limited to 15 in program).
L = Number of local point, from 1 to NL.
NMAT = Total number of materials (limited to 3 in program).
M = Number of material, from 1 to NMAT.
T = Temperature for each point at the present time step.
T' = Temperature for the point at the previous time step.

The temperature increment, ΔT, for any point is the temperature difference between the present and previous time steps.

$$\Delta T = T - T' \tag{42}$$

Then temperature increments between local layer and other layers at previous time step are defined.

$$D_1 = T'_{L+1} - T'_L \tag{43}$$

$$D_2 = T'_{L-1} - T'_L \tag{44}$$

$$D_3 = T'_3 - T'_1 \tag{45}$$

For all cases, heat in = heat out + heat stored, or $q_{in} = q_{out} + q_{stored}$

(1) Multi-Slab Materials. The multi-slab materials are shown in Figure 7.

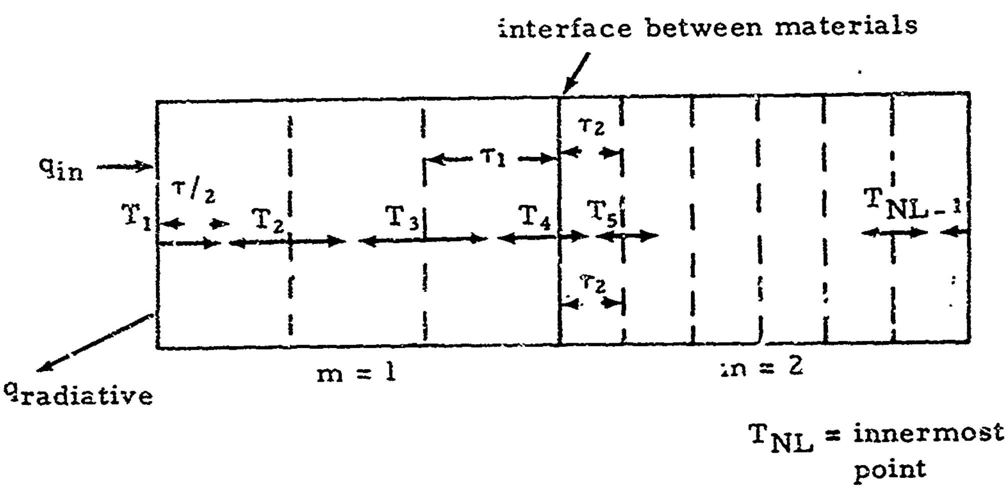

Figure 7. Multi-Slab Materials

(2) Heat Balance at the Air Flow Side of Slab. Heat in = $q_{in} = H\,(T_{rec} - T_1)$ = Aerodynamic heat transfer rate. Heat out is the heat transfer to surrounding atmosphere plus the heat transfer to the next thickness.

$$q_{out} = \epsilon\sigma\,(T_1 - T_\infty)^4 + k\,(T_1 - T_2)/\tau$$

Heat stored is the heat remaining in the first thickness:

$$q_{stored} = 0.5\ \Delta T_1 / F_1$$

$$T_{rec} = T_s \left[1 + 0.5\ (\gamma_s - 1)\ R\ M_s^2 \right] . \tag{46}$$

For a Sphere: $\gamma_s = 1.4$.

For a F. P. or Cone: γ_s is defined by Equation (57).

Equation (28) defined Q_w for a sphere when the local velocity is greater than 6000 ft/sec, but for other cases,

$$Q_w = H\,(T_{rec} - T_1) \tag{47}$$

$$\dot{Q} = Q_w - \epsilon\sigma\ (T_1/100)^4 . \tag{48}$$

With the heat balance $q_{in} = q_{out} = q_{stored}$, the outside skin transient temperature for a slab is

$$T_1 = T_1' + 2\left[F_1 \dot{Q} + B_1 D_1 \right] . \tag{49}$$

(3) <u>Heat Balance Around Interior Points.</u>

$$q_{in} = k\,(T_{m-1} - T_m) / \tau_m$$

$$q_{out} = k\,(T_m - T_{m-1}) / \tau_m$$

$$q_{stored} = \frac{\rho C_p \tau}{\Delta t}\ (T - T') .$$

The temperature at each small layer within the material is

$$T_L = T_L' + B_m \left[D_1 + D_2 \right] \tag{50}$$

where

$$L = 2, 3 \ldots (NL-1).$$

(4) Heat Balance at Interface.

$$T_L = T'_L + 2\left[\frac{D_2 + F_m D_1}{\frac{1}{B_{m-1}} + \frac{F_m}{B_m}}\right] \tag{51}$$

where L is the point between materials m and m-1.

(5) Heat Balance at Innermost Point.

$$T_{NL} = T'_{NL} + 2\, B_m\, D_2 \tag{52}$$

(6) Thin-Wall Followed by Multi-Slab Materials. The thin-wall followed by multi-slab materials is shown in Figure 8.

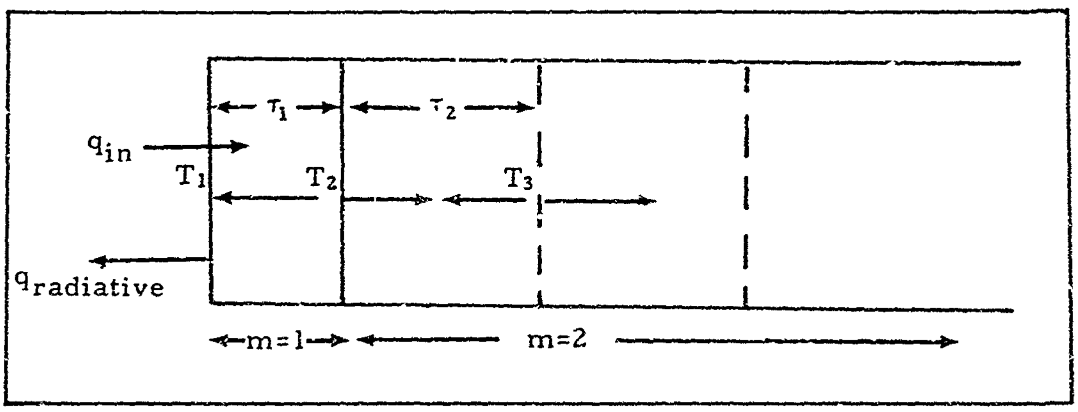

Figure 8. Thin-Wall Followed by Multi-Slab Materials

For a thin outer wall, when $NLAY_1 = 1$.

$$q_{in} = H\,(T_{rec} - T_1)\ ,$$

where T_{rec} is defined by Equation (46)

$$q_{out} = q_{radiative} + D_3$$

and

$$q_{stored} = \left[\frac{(\rho c_p \tau)_2}{2\Delta t} + \frac{1}{F_1}\right](T_1 - T_1')\ .$$

Then

$$T_1 = T_1' + \frac{\tau_2 \dot{Q} + k_2 D_3}{0.5\, k_2/B_2 + \tau_2/F_1} \tag{53}$$

For a thin wall, the temperature is assumed to be constant through the entire thickness, thus

$$T_2 = T_1 \tag{54}$$

(7) Multi-Slab Materials Followed by a Thin Wall. The multi-slab materials followed by a thin wall are shown in Figure 9.

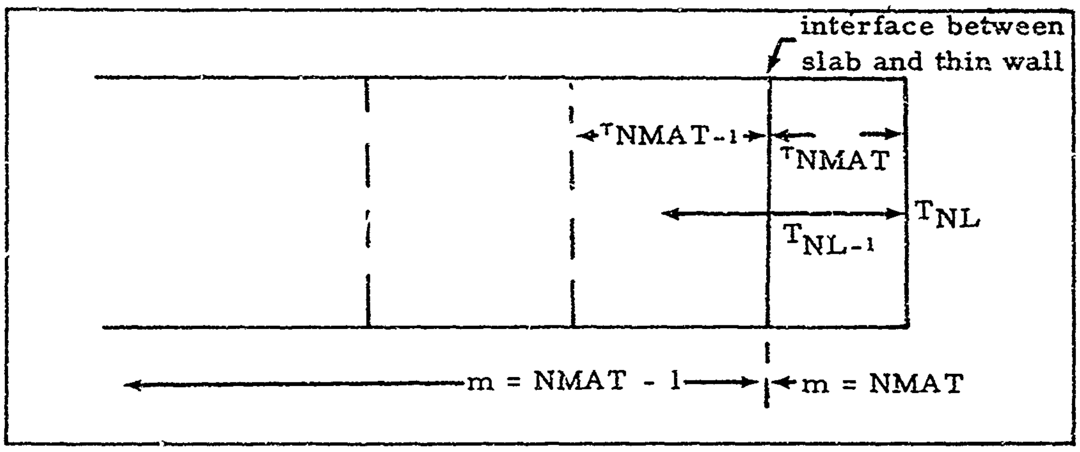

Figure 9. Multi-Slab Materials Followed by a Thin Wall

For a thin inner wall, when $NLAY_{NMAT} = 1$:

$$T_{NL-1} = \frac{2D_2}{\frac{1}{B_{m-1}} + \frac{2F_m}{B_m}} \tag{55}$$

where m = innermost material = NMAT,

then

$$T_{NL} = T_{NL-1} ,$$

since the temperature is assumed constant through the thin material.

e. Specific Heat Ratios for Air

A correlation for specific heat ratio for air is

$$C_p = f(T) \qquad (56)$$

Where T =	0	C_p =	0.24
=	800	=	0.24
=	1700	=	0.27
=	3000	=	0.29
=	5000	=	0.31
=	9000	=	0.32
=	11,700	=	0.40
T =	14,400	C_p =	0.46

$$\gamma_{local} = C_p / \left[C_p - R_g / J \right] \qquad (57)$$

where

$$J = 778 \frac{ft - lb}{Btu} x\, g_a .$$

f. Flight Environment

The IBM 1620 digital computer program has the ARDC 1959 atmosphere subroutine as an integral part of the transient aerodynamic heat transfer calculation. Appendix B describes this subroutine. In addition, a constant altitude and/or constant local flow properties flight environment, such as wind tunnel testing, is included in the computer routine for flat plate or cone. The symbol, NCFIT, determines whether trajectory data or a constant value for altitude is used. If NCFIT is given 0, constant altitude, local Mach number, pressure, and temperature are given.

3. Conclusions

The aerodynamic heat transfer and transient temperature distribution computer program described in this report provides an economical preliminary design capability for heat transfer analysis. Comparison of transient temperatures with PERSHING Ballistic Missile flight test data[5] and with more sophisticated aerodynamic heat transfer digital computer programs indicates very good agreement.

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Appendix A

FORTRAN PROGRAM AND ITS USAGE

1. Fortran Program Statements

```
C      TEMPERATURE VS TIME FOR LAYFRS OF SPHFRE, FLAT PLATE, OR CONE
C      COMPILED ON IBM 1620 40K BEGINNING AT 08200
C      SW 1 ON -- FOR CARD OUTPUT AT ALL TIME STEPS
C      SW 2 ON -- FOR CARD INPUT OF -------- DTIME, DTOUT, TLO, THI
C      SW 2 OFF - FOR TYPEWRITER INPUT OF -- DTIME, DTOUT, TLO, THI
C      SW 3 ON  - TO END RUN, OUTPUT LAST STEP, BRANCH TO NEXT CASE
C      TBODY = TYPF OF BODY
C            = 1.0 FOR SPHERE        --  NCFIT = 2,
C            = 2.0 FOR FLAT PLATE    --  NCFIT = 5  OR 0
C            = 3.0 FOR CONE          --  NCFIT = 5  OR 0
C      NCFIT = NO. OF CURVES FITTED --
C            = 0  FOR F.P. OR CONE -- GIVEN CONSTANT LOCAL M, P, T, ALT
C            = 2 OR 5  -- CURVES FITTED ARF ----------
C                          1.  ALTITUDF  VS  TIMF
C                          2.  VELOCITY  VS  TIME
C                          3.  LOCAL M   VS  FREE STREAM MACH NUMBER
C                          4.  PS/PF VERSUS  FREE STREAM MACH NUMBFR
C                          5.  TS/TF VERSUS  FREE STREAM MACH NUMBER
C      SPHERE ------   TH=POSITION ANG, RNORY=NOSE RADIUS, QRRET= Q RATIO
C      F.P. OR CONE -- TH=IDENTIFYING ANG, RNORY=SURFACE L, QRRET=RET
C      NMAT  = NUMBER OF MATFRIALS -- 1, 2, OR 3
C      NL    = TOTAL NUMBER OF SKIN LAYERS + END POINT -- MAXIMUM = 15
C      SUBSCRIPTS--S FOR LOCAL--F FOR FRFE STREAM
1000   FORMAT (1H )
1001   FORMAT (1H 42H  TEMPERATURE VS TIME FOR LAYERS OF SPHERE)
1002   FORMAT (1H 46H  TEMPERATURE VS TIME FOR LAYERS OF FLAT PLATE)
1003   FORMAT (1H 40H  TEMPFRATURE VS TIMF FOR LAYERS OF CONE)
1004   FORMAT (1H 20H  DTIME FOR EACH MAT)
1005   FORMAT ( 4E15.8, 1I5)
1024   FORMAT (1H 48H SW1 OUTS ALL STEPS--SW2 CARD INPUTS 4 TIME VALS)
1025   FORMAT (1H 18H --- SW 3 ENDS RUN)
1034   FORMAT (1H 45H INPUT--DTIME,DTOUT,TLO,THI--ON 4 LINES BY TY!
1054   FORMAT (1H 22H APP 1620 MIN REQUIRED)
1006   FORMAT ( 1I5)
1007   FORMAT ( 1E15.5, 1I5)
1008   FORMAT (1H 49H  DTIME=          DTOUT=          TLO=        THI=)
1009   FORMAT (1H 37H  THETA=          Y=              RET=)
1010   FORMAT (1H 36H  THETA=          RN=             QR=)
1011   FORMAT (1H 44H  TMELT=          QEFF=           FMISSIVIYY=)
1012   FORMAT (1H 46H  MATERIAL -- DTIME, M, K, RHO, CP, TAUT, NLAY)
1013   FORMAT (1H 35H  --- FOR EACH OUTPUT TIME STEP ---)
1014   FORMAT (1H 39H  TIME       ALT,KFT   VEL,FT/SEC      RE)
1015   FORMAT (1H 49H  QW         QDOT       H      TAUAB --- HEAT COEFFS)
1016   FORMAT (1H 42H  MACH NO.  PRESSURE  TEMPERATURE -- LOCAL)
1017   FORMAT (1H 48H  MACH NO.  PRESSURE  TEMPERATURE -- FREE STREAM)
1018   FORMAT (1H 43H  TEMPFRATURF AND COUNT FOR EACH SKIN LAYFR)
1019   FORMAT (1H 42H  TIME, ALT, VEL --- AT WALL MELTING POINT)
       DIMENSION  AP(11,3),TEMP(15),TEMPL(15),CON(6,15),NUM(5)
       DIMENSION  RHO(3),CP(3),TAU(3),C(3),F(3),F(3),V(5)
C      READ ATMOSPHERIC PROPFRTIES FROM AP TABLE OF APPENDIX B
       DO 1  K=1,11
       READ  1005,  ALT,       TF,        PF
       AP(K,1) = ALT * 3.2808333                                    (B-1)
       AP(K,2) = TF  * 1.8                                          (B-2)
1      AP(K,3) = PF  * .0208854                                     (B-3)
       PRINT 1024
       PRINT 1025
```

```
C     INPUT FOR EACH CASE -- BEGINS AT STATEMENT 2
2     PUNCH 1000
      PUNCH 1000
      READ  1007,  TBODY,     NCFIT
      READ  1005,  TH,        RNORY,    QRRET
      READ  1005,  TMELT,     QE,       E
      Y   = RNORY
      RET = QRRET
      PRINT 1000
      PRINT 1000
      IF (TBODY-2.0 ) 301, 302, 303
301   PUNCH 1001
      PRINT 1001
      PUNCH 1000
      PUNCH 1010
      QR   = QRRET
      SQRD = (2.*RNORY)**.5
      Z2 = 1.522036+TH*(1.536913E-03+TH*(-3.701802E-04+TH*2.688E-06)) (9)
      PSVPT = 1.0 - .957*SIN(TH/57.29578)**2                          (24)
      GO TO 304
302   PUNCH 1002
      PRINT 1002
      PUNCH 1000
      PUNCH 1009
      HX = 1.0
      GO TO 304
303   PUNCH 1003
      PRINT 1003
      PUNCH 1000
      PUNCH 1009
      HX = 3.0 ** .5                                                  (32)
304   PUNCH 1005,  TH,        RNORY,    QRRET
      PUNCH 1000
      PUNCH 1011
      PUNCH 1005,  TMELT,     QE,       E
      PUNCH 1000
      PUNCH 1012
      PRINT 1000
      PRINT 1004
      READ  1006,  NMAT
      NL = 1
C     MATERIALS LOOP -- COMPUTE MINIMUM DTIME FOR EACH MATERIAL
      V2 = 10.
      DO 4  M=1,NMAT
      READ 1005,   C(M),     RHO(M),    CP(M),    TAUT,     NUM(M)
      V1 = NUM(M)
      TAU(M) = TAUT/V1                                                (37)
      NL=NL+NUM(M)
      NUM(M+1) = 0.0
      F(M) = RHO(M)*CP(M)*TAU(M)
      TEMP(M) = C(M)/TAU(M)
      DTIME = .5*F(M)/(TEMP(M)+V2)                                    (38)
      V2 = 0.0
      PRINT 1007,  DTIME,     M
      PUNCH 1007,  DTIME,     M
4     PUNCH 1005,  C(M),     RHO(M),    CP(M),    TAUT,     NUM(M)
      IF (SENSE SWITCH 2 ) 400, 401
400   READ  1005,  DTIME,     DTOUT,    TLO,      THI
      GO TO 402
```

```
401   PRINT 1034
      ACCEPT 1005,      DTIME
      ACCEPT 1005,      DTOUT
      ACCEPT 1005,      TLO
      ACCEPT 1005,      THI
402   NT = (THI-TLO)/DTIME + 1.                            (A-1)
      T1620 = NT/10 *NL/4                                  (A-11)
      PRINT 1054
      PRINT 1005,  T1620
      PUNCH 1000
      PUNCH 1008
      PUNCH 1005,  DTIME,    DTOUT,    TLO,      THI
      DO 6  M=1,NMAT
      F(M) = DTIME/F(M)                                    (39)
      B(M) = F(M)*TEMP(M)                                  (41)
      IF(M-1) 5, 6, 5
5     F(M) = TEMP(M)/TEMP(M-1)                             (40)
6     CONTINUE
      NL1=NUM(1)
      NL2=NUM(2)
C     READ INITIAL TEMPERATURES  AND COUNT
      DO 7  L=1,NL
7     READ  1007,   TEMPL(L),          L1
      G = 1.4
      GM1 = G-1.
      GP1 = G+1.
      G1  = 1./GM1
      G2  = 2./GM1
      RG = 1716.
      GA = 32.174
      QAB = 0.0
      TAUAB=0.0
      ABOUT=0.0
      PUNCH 1000
      IF (NCFIT) 9, 8, 9
C     CONSTANT LOCAL VALUES GIVEN
8     READ  1005,  ALT,      VEL
      READ  1005,  SM,       PS,       TS
      PUNCH 1016
      PUNCH 1005,  SM,       PS,       TS
9     PUNCH 1000
      PUNCH 1013
      PUNCH 1014
      PUNCH 1015
      IF (NCFIT) 10, 11, 10
10    PUNCH 1016
      PUNCH 1017
11    PUNCH 1018
      PUNCH 1000
      TIME = TLO
      N = 0
C     TIME STEP LOOP  -- N=COUNTER
110   N = N + 1
      TW = TEMPL(1)
      L1 = 1
      X  = TIME                                            (A-2)
      IF (NCFIT) 12, 40, 12
C     CURVE FITS DATA LOOP
12    DO 35  I=1,NCFIT
```

```
      IF (N-1) 15, 13, 15
13    READ  1006,  NUM(I)
      L2 = NUM(I)+L1-1
      DO 14  L=L1,L2
      READ  1005,  CON(1,L), CON(2,L)
14    READ  1005,  CON(3,L), CON(4,L), CON(5,L), CON(6,L)
15    L2 = NUM(I) + L1 - 1
      DO 20  L=L1,L2
      IF(X-CON(2,L)) 22, 22, 20
20    CONTINUE
      L  = L-1
22    L1 = L2 + 1
      FX = (X-CON(1,L))/(CON(2,L)-CON(1,L))                            (A-5)
      V(I) = CON(3,L)+FX*(CON(4,L)+FX*(CON(5,L)+FX*CON(6,L)))          (A-4)
      IF (I-2) 35, 23, 35
23    ALT = V(1)                                                       (A-6)
      VEL = V(2)
      ALTF = 20856000.*ALT/(20856.+ALT)                                (A-7)
                                                                       (B-4)
      DO 25  K=2,11
      IF(ALTF-AP(K,1)) 26, 25, 25
25    CONTINUE
26    K  = K-1
      DALT = ALTF-AP(K,1)                                              (B-5)
      TS = (AP(K+1,2)-AP(K,2))/(AP(K+1,1)-AP(K,1))                     (B-7)
      TF = AP(K,2)+DALT*TS                                             (B-6)
      PF = AP(K,3)/EXP(.01879*DALT/AP(K,2))                            (B-8)
      IF(TS) 27, 28, 27
27    PF = AP(K,3)*(AP(K,2)/TF)**(.01879/TS)                           (B-11)
28    DF = .01879*PF/TF                                                (B-13)
      FMSQ = VEL*VEL/ (RG*G*TF)
      FM = FMSQ**.5                                                    (B-14)
      X = FM                                                           (A-3)
      IF ( TBODY-1. ) 35, 30, 35
C     SPHERE -- LOCAL M, P, T
30    SMSQ = G2*(PSVPT**(-GM1/G)-1.0)                                  (25)
      SM = SMSQ**.5
      PS = PF*PSVPT*(.5*GP1*FMSQ)**(G/GM1)*(GP1/(2.*G*FMSQ-GM1))**G1   (23)
      TS = TF*(G2+FMSQ)/(G2+SMSQ)                                      (27)
      TV = TW
      GO TO 41
35    CONTINUE
C     FLAT PLATE OR CONE -- LOCAL M, P, T
      SM = V(3)                                                        (A-8)
      PS = V(4)*PF                                                     (A-9)
      TS = V(5)*TF                                                     (A-10)
40    TV = TS
      SMSQ = SM*SM
C     TREF AND COP -- FOR ALL CASES
C     RE, CPS, CPREF, AND NEW GAMMA -- FOR CONE OR FLAT PLATE
41    TREF = .5*(TW+TS*(1.0+.078*SMSQ))                                (11)
      URFF = .249E-06 *TREF**0.63 / GA                                 (13)
      CREF = 11.997 * URFF                                             (12b)
      IF (TREF-1000.) 410, 411, 411
410   CREF = .23791763E-06 * TREF**1.52   (TREF+198.6)                 (12a)
411   DO 50  I=1,2
      COP = .24                                                        (56)
      IF(TV-800.) 46, 46, 42
42    V(1) = .219756
      V(2) = .00002669
```

```
      V(3) =-.172760F-08
      IF (TV-9000.) 45, 45, 43
43    V(1) =-.091110
      V(2) = .00005802
      V(3) = .137174E-08
45    COP = V(1) + TV * ( V(2) + TV * V(3) ,
46    GL = COP/(COP-.06857326)                                          (56)
      CPREF = COP                                                       (57)
      PRREF = UREF * CPREF / CREF * GA
      IF (I-1) 50, 48, 50                                               (14)
48    CPS = COP
      RE = 1063446.*PS*SM*Y *GL**.5*(TS+198.6)/TS**2
      TV = TREF                                                         (36)
      IF (TBODY-1.0) 50, 70, 50
50    CONTINUE
C     FLAT PLATE OR CONE -- LAMINAR CONSTANTS
      R  = 0.85
      CC = .332
      EX = 0.5                                                          (30)
      IF (RE-RET) 60, 60, 52                                            (31)
C     FLAT PLATE OR CONE -- TURBULENT CONSTANTS
52    R  = 0.892
      CC = .01396
      EX = 0.85                                                         (33)
      IF (TBODY-3.) 60, 54, 60                                          (34)
54    HX = 2./3.**.5
C     FLAT PLATE OR CONE -- HEATING COEFFICIENTS                        (35)
60    H = ((TS*GL/ RG )**.5*PS*SM/TREF)**EX
      H = CC* GA *HX *H*(UREF/Y )**(1.-EX) * CPS/PRREF**.66666667       (29)
      GO TO 79
70    RE = 0.0
      IF(VEL-6000.) 78, 76, 76
C     SPHERE -- VELOCITY EQUAL TO OR GREATER THAN 6000 FT/SEC
76    QW =   6006.*TF + .5*VEL*VEL
      QW = ( QW-778.*GA*COP*TW)/(QW-3244100.)*(VEL/10000.)**3.15*DF**.5
      QW = 4413.4104   * QW * QR / SORD
      H = 0.0                                                           (28)
      GO TO 80
C     SPHERE -- VELOCITY LESS THAN 6000 FT/SEC
78    R = .85
      GL = G
      Z1 = ((1.4+7./FMSQ)*( .139*(7.-1./FMSQ))**2.5)**.25
      Z3 = CREF*PRREF**.4/(TREF*UREF)**.5                               (8)
      H  = .5 * Z1 * Z2 * Z3 * (VEL*PS/RG )**.5 / SORD                  (10)
79    TREC = TS*(1.+.5*(GL-1.)*R*SMSQ)                                  (15)
      QW = H * (TREC-TW)                                                (46)
80    QDOT = QW-E*(TW/100.)**4*.48096E-05                               (47)
      M  = 1                                                            (48)
      IF (N-1) 800, 94, 800
C     LAYER TEMPERATURE LOOP
800   DO 92  L=1,NL
      IF (L-1) 83, 81, 83
C     WALL TEMPERATURE INCREMENT
81    DTEMP = 2.*(F(M)*QDOT+B(M)*(TEMPL(2)-TEMPL(1)))
      IF(NL1-1) 89, 82, 89                                              (49)
C     THIN WALL TEMPERATURE INCREMENT
82    DTEMP = TEMPL(3)-TEMPL(1)
      DTEMP = (TAU(2)*QDOT+C(2)*DTEMP)/(.5*C(2)/B(2)+TAU(2)/F(1))       (45)
      TEMP(1) = TEMPL(1)+DTEMP
                                                                        (53)
```

```
      L = 2                                                            (54)
      GO TO 89
83    D2 = TEMPL(L-1) - TEMPL(L)                                       (44)
C     END POINT TEMPERATURE INCREMENT
      DTEMP = 2.*B(M)*D2                                               (52)
      IF(L-NL) 84, 89, 84
84    D1 = TEMPL(L+1)-TEMPL(L)                                         (43)
C     INTERIOR TEMPERATURE INCREMENT
      DTEMP = B(M) * (D1+D2)                                           (50).
      IF ( NL1+1-L ) 86, 85, 89
85    M  = 2
      GO TO 88
86    IF ( NL1+NL2+1-L) 89, 87, 89
87    M  = 3
C     INTERFACE TEMPERATURE INCREMENT
88    DTEMP = 2. * (( D1*F(M)+D2) / (1./B(M-1)+F(M)/B(M)))             (51)
      IF (NL-1-L) 89, 880, 89
C     INTERFACE AND END POINT TEMP INCREMENT FOR THIN INNER MATERIAL
880   DTEMP = 2.*D2/(1./B(M-1)+2.*F(M)/B(M))
      TEMP(L) = TEMPL(L) + DTEMP                                       (55)
      L = NL
C     LOCAL TEMPERATURE
89    TEMP(L) = TEMPL(L)+DTEMP
      IF(TEMP(L)-TMELT) 92, 900, 900
900   TEMP(L) = TMELT
      IF (L-1) 92, 90, 92
C     MELTING POINT FOR WALL
90    QAB = QAB+QDOT*DTIME                                             (A-12)
      TAUAB = 12.*QAB/(QE*RHO(1))                                      (A-13)
      IF (ABOUT) 92, 91, 92
91    PUNCH 1019
      PUNCH 1006,  N
      PUNCH 1005,  TIME,     ALT,      VEL
      ABOUT = 1.0
92    CONTINUE
      DO 920  L=1,NL
920   TEMPL(L) = TEMP(L)
      IF (SENSE SWITCH 3) 95, 921
921   IF(SENSE SWITCH 1)  95,93
93    IF(TPRNT-DTOUT)  99,94,99
94    TPRNT=0.0
95    PUNCH 1006,     N
      PUNCH 1005,  TIME,     ALT,      VEL,      RE
      PUNCH 1005,  QW,       QDOT,     H,        TAUAB
      IF(NCFIT)  97,97,96
96    PUNCH 1005,  SM,       PS,       TS
      PUNCH 1005,  FM,       PF,       TF
97    DO 98  L=1,NL
98    PUNCH 1007,  TEMPL(L),      L
99    TIME= TIME +DTIME
      TPRNT=TPRNT+DTIME
      IF (SENSE SWITCH 3) 2, 100
100   IF (TIME-THI) 110, 110, 2
      END
```

2. Input Format

	Floating Point Data				Fixed Point Data			Number of Times Needed
Comment #	Column # 1 - 15	16 - 30	31 - 45	46 - 60	4 - 5	19 - 20	64 - 65	
1	ALT, m	T, °K	P, $\frac{Newtons}{M^2}$					Read 11 AP Cards Only Once
2	TBODY					NCFIT		Each Case
3	θ	RN or Y	QR or RET					
4	$TMELT_w$	Q_{eff}	ϵ					
5					NMAT			
6	λ_m	ρ_m	C_{p_m}	$TTOT_m$			$NLAY_m$	Each Material
7	DTIME	DTOUT	TLO	THI				
8	$TEMP_L$					L1		Each Layer + End Point
9					NSEG			
10	XLO	XHI						Each Curve When NCFIT ≠ 0; Each Segment
11	A_0	A_1	A_2	A_3				
12	ALT	VEL						When NCFIT = 0
13	M_s	P_s	T_s					

3. Input Comments

1) Eleven Atmospheric Properties Data Cards, as described in Appendix B

2)

	TBODY =	NCFIT =
Sphere	1.	2
Flat Plate	2.	5 or 0
Cone	3.	5 or 0

When NCFIT $\neq$ 0, the curves needed are

Curve I: ALT, ft vs Time, sec — Sphere, FP or Cone

Curve II: VEL, ft/sec vs Time, sec — Sphere, FP or Cone

Curve III: M_s vs M_∞ — FP or Cone

Curve IV: P_s/P_∞ vs M_∞ — FP or Cone

Curve V: T_s/T_∞ vs M_∞ — FP or Cone

3) Sphere: θ RN QR

FP or Cone: θ Y RET

(θ is used for identification only for flat plate or cone)

4) Melting temperature effective heat of ablation and emissivity of wall material.

5) Number of materials = 1, 2, or 3.

6) Material properties, where m = 1 to NMAT. Sum of layers cannot exceed 14. NLAY cannot = 2.

7) Time inputs: By card - SW 2 ON. By typewriter on 4 lines - SW 2 OFF

NT = Total number of time steps

$$NT = (THI-TLO)/DTIME + 1. \quad (A-1)$$

8) Initial temperatures for each layer and end point. L1 is input as convenience to use output TEMP cards to restart - does not necessarily equal L.

9) Number of segments of the curve. Total number of segments for all curves cannot exceed 15.

10) Limits of segment:

$$X = \text{Time, for Curves 1 and 2} \quad (A-2)$$

$$X = M_\infty\text{, for Curves 3, 4, and 5} \quad (A-3)$$

11) Coefficients of the normalized cubic equation:

$$V_i = A_0 + A_1(FX) + A_2(FX)^2 + A_3(FX)^3 \qquad \text{(A-4)}$$

where

$$F_x = (X - XLO)/(XHI - XLO) \qquad \text{(A-5)}$$

and

$$V_1 = ALT \qquad \text{(A-6)}$$

$$V_2 = VEL \qquad \text{(A-7)}$$

$$V_3 = M_s \qquad \text{(A-8)}$$

$$V_4 = P_s/P_\infty \qquad \text{(A-9)}$$

$$V_5 = T_s/T_\infty \qquad \text{(A-10)}$$

12) Constant local conditions, given for flat plate or cone when NCFIT = 0. ALT and VEL are used for identification only.

4. IBM 1620 Operating Instructions

a. Compiling and Starting

1) Compile Fortran program on IBM 1620 40K digital computer starting at 08200 memory core.
2) Load object deck. Check console switches.

b. Console Switches

1) SW1 ON For output at all time steps
2) OFF For output only at time steps determined by DTOUT
3) SW2 ON Card input of time values--DTIME, DTOUT, TLO, THI
4) OFF Typewriter input of these values
5) SW3 ON Ends run, prints last time step, branches to next case
6) SW4 OFF During typewriter input
7) ON To make corrections in typewriter input

c. Typewriter Output and Input

The time increment, Δt or DTIME, is calculated for each material and printed. Operator determines Δt from smaller value, then inputs four time values by typewriter--unless SW2 is ON. The computed values for DTIME should be approximately the same for all materials used. DTOUT must be an exact multiple of DTIME.

A rough estimate of the machine time which will be required is printed. This enables the operator to leave the machine and plan for additional machine time, if necessary.

$$T1620 = NT \times NL/40 \qquad \text{(A-11)}$$

Typewriter input and output for a sphere (Example 1) follows:

```
SW1 OUTS ALL STEPS--SW2 CARD INPUTS 4 TIME VALS
     SW3 ENDS RUN

 TEMPERATURE VS TIME FOR LAYERS OF SPHERE

DTIME FOR EACH MAT
274.09802E-04          1
300.54519E-04          2
317.39871E-04          3
INPUT--DTIME, DTOUT, TLO, THI--ON 4 LINES BY TY
  .025RS
  .5RS
  16.RS
  18.RS
APP 1620 MIN REQUIRED
.13000000E+02
```

d. After Ablation

When the wall temperature reaches the given melting temperature, TMELT, ablation begins. After this point the computed values for the temperatures of each layer may be doubtful since only a simple procedure is included for this ablation.

$$Q_{AB} = \Sigma\,(Q\,\Delta t), \text{ while } T_w \geqq \text{TMELT} \qquad \text{(A-12)}$$

$$\tau_{AB} = 12\,Q_{AB} / (Q_{eff}\,\rho_1) \qquad \text{(A-13)}$$

e. Terminating and Restarting

The problem may be terminated before reaching the upper time limit, TH1, and started again later as follows:

1) To terminate: Turn SW1 ON to putput values at all time steps--to determine suitable TIME to restart. (SW3 on outputs last time values only then branches to next case) Save the cards for temperatures at each layer.

2) To begin again: The original input values are used except TLO = TIME and initial temperatures for each layer and end point are from last time step computed. The time values: DTIME, DTOUT, TLO, and TH1 may be input on one card, instead of by typewriter, if SW2 is ON.

5. Example Runs for Sphere, Flat Plate, and Cone

Case 1 is a sphere consisting of three materials: beryllium (4 layers), molybdenum (3 layers) and a thin inner wall of aluminum. The nose radius is one foot and the position angle is zero degrees. An initial time of 16 seconds is given to utilize all heat coefficient equations--those for velocities less and greater than 6000 ft/sec. Typewriter input is used for DTIME, DTOUT, TLO and THI for Case 1 only.

Case 2 is a 4° flat plate, with Y = 2 feet, and composed of a thin wall of beryllium and a slab of molybdenum. Altitude and velocity data are the same as for Case 1. With initial time of 16 seconds and transition Reynolds number of 22500000 both laminar and turbulent boundary layer equations are used.

Case 3 is a 4° cone with all input data the same as for Case 2, except no curve fit data are used. Constant altitude, velocity and local properties are given.

6. Input Data for Examples

(Switch 1 on for first steps)
(Switch 2 on for Cases 2 and 3)

0.	288.16	101325.	AP59 1
11000.	216.66	22632.	AP59 2
25000.	216.66	2488.6	AP59 3
47000.	282.66	120.444	AP59 4
53000.	282.66	58.3215	AP59 5
79000.	165.66	1.00946	AP59 6
90000.	165.66	.104438	AP59 7

```
    105000.      225.66      .745265E-02                    AP59  8
    160000.     1325.66      .362003E-03                    AP59  9
    170000.     1425.66      .282362E-03                    AP59 10
    700000.     3325.66      .000000                        AP59 11
      1.0        2                                          SPHERE
 0.0             1.0         1.0
 2805.           3000.       0.8
      3
 .01347          114.9       .6968        .032      4       BERYL
..01747          636.8       .0634        .0153     3       MOLY
 .02333          168.6       .2440        .006      1       ALUM
 540.            1
 540.            1
 540.            1
 540.            1
 540.            1
 540.            1
 540.            1
 540.            1
 540.            1
      1
 0.0             18.
 300.           -255.25706   48.9861     -93.729
      1
 0.0             18.
 16000.          4370.0192  -16559.985   -810.016
      2.0        5                                          FLAT P
 4.0             2.         22500000.
 2805.           3000.       0.8
      2
 .01347          114.9       .6968        .008      1       BERYL
 .01747          636.8       .0634        .0153     3       MOLY
      .025       .50         16.          18.
 540.            1
 540.            1
 540.            1
 540.            1
 540.            1
      1
 0.0             18.
 300.           -255.25706   48.9861     -93.729
      1
 0.0             18.
 16000.          4370.0192  -16559.985   -810.016
      4

    32
```

1.5	3.0				
1.4690000	1.4689996	-.013494600	-.00450200		
3.0	6.0				
2.92	2.8634991	-.09449200	-.00000500		
6.0	10.				
5.689	3.5613287	-.18000000	-.00532700		
10.	20.				
9.065	7.9674930	-1.2445000	.03500000		
4					
1.5	3.0				
1.045	.07599960	-.02249760	.03149860		
3.0	6.0				
1.13	.19699980	.09450330	-.03150230		
6.0	10.				
1.39	.49766601	-.05000000	.10933290		
10.	20.				
1.947	1.5800819	.95175000	-.13583300		
4					
1.5	3.0				
1.01231	.01994460	.00153250	.00139350		
3.0	6.0				
1.0351800	.05312460	.01116250	-.00076650		
6.0	10.				
1.0987000	.09385967	.0208000	-.00416070		
10.	20.				
1.2092	.31294110	.09418250	.00802500		
3.0	0				CONE
4.0	2.	22500000.			
2805.	3000.	0.8			
2					
.01347	114.9	.6968	.008	1	BERYL
.01747	636.8	.0634	.0153	3	MOLY
.025	.50	16.	18.		
540.	1				
540.	1				
540.	1				
540.	1				
540.	5				
45.98	6231.				
6.076376	425.852	432.5785			

7. Output Data for Examples

a. Temperature versus Time for Layers of Sphere

```
 THETA=           RN=               QR=
.00000000E-99   .10000000E+01     .10000000E+01

 TMELT=           QEFF=             EMISSIVITY=
.28050000E+04   .30000000E+04     .80000000E-00

 MATERIAL -- DTIME, M, K, RHO, CP, TAUT, NLAY
274.09802E-04     1
.13470000E-01   .11490000E+03     .69680000E-00    .80000000E-02      4
300.54519E-04     2
.17470000E-01   .63680000E+03     .63400000E-01    .51000000E-02      3
317.39871E-04     3
.23330000E-01   .16860000E+03     .24400000E-00    .60000000E-02      1

 DTIME=           DTOUT=            TLO=             THI=
.25000000E-01   .50000000E-00     .16000000E+02    .17500000E+02


 **- FOR EACH OUTPUT TIME STEP ---
 TIME         ALT,KFT    VEL,FT/SEC       RE
 QW           QDOT         H       TAUAB --- HEAT COEFFS
 MACH NO.     PRESSURE   TEMPERATURE -- LOCAL
 MACH NO.     PRESSURE   TEMPERATURE -- FREE STREAM
 TEMPERATURE AND COUNT FOR EACH SKIN LAYER


   1
.16000000E+02   .45981030E+02     .62311290E+04    .00000000E-99
.83836260E+02   .83832989E+02     .00000000E-99    .00000000E-99
.00000000E-99   .15872714E+05     .36223364E+04
.64375182E+01   .29491558E+03     .38998800E+03
540.00000E-00     1
540.00000E-00     2
540.00000E-00     3
540.00000E-00     4
540.00000E-00     5
540.00000E-00     6
540.00000E-00     7
540.00000E-00     8
540.00000E-00     9
   2
.16025000E+02   .45438510E+02     .61936070E+04    .00000000E-99
.83333656E+02   .83330385E+02     .00000000E-99    .00000000E-99
.00000000E-99   .16097295E+05     .35835250E+04
.63987534E+01   .30269147E+03     .38998800E+03
546.50511E-00     1
540.00000E-00     2
540.00000E-00     3
540.00000E-00     4
540.00000E-00     5
540.00000E-00     6
540.00000E-00     7
540.00000E-00     8
540.00000E-00     9
   3
   .
   .
   .
```

```
  7
.16150000E+02   .42714160E+02   .60049130E+04   .00000000E-99
.79992499E+02   .79988578E+02   .00000000E-99   .00000000E-99
.00000000E-99   .17253935E+05   .33919010E+04
.62038092E+01   .34495806E+03   .38998800E+03
568.40264E-00     1
544.48412E-00     2
540.41221E-00     3
540.02213E-00     4
540.00094E-00     5
540.00007E-00     6
540.00000E-00     7
540.00000E-00     8
540.00000E-00     9
  8
.16175000E+02   .42166950E+02   .59669560E+04   .00000000E-99
.88532884E+02   .88528868E+02   .31781561E-01   .00000000E-99
.00000000E-99   .17491837E+05   .33540708E+04
.61645947E+01   .35413596E+03   .38998800E+03
572.16971E-00     1
545.78844E-00     2
540.65418E-00     3
540.04637E-00     4
540.00287E-00     5
540.00040E-00     6
540.00002E-00     7
540.00000E-00     8
540.00000E-00     9
  9
.16200000E+02   .41618950E+02   .59289280E+04   .00000000E-99
.87703263E+02   .87699140E+02   .31959027E-01   .00000000E-99
.00000000E-99   .17731926E+05   .33164104E+04
.61253071E+01   .36357234E+03   .38998800E+03
575.54830E-00     1
547.18479E-00     2
540.95165E-00     3
540.08345E-00     4
540.00669E-00     5
540.00126E-00     6
540.00016E-00     7
540.00000E-00     8
540.00000E-00     9
 10
.16225000E+02   .41070170E+02   .58908270E+04   .00000000E-99
.86877063E+02   .86872841E+02   .32136568E-01   .00000000E-99
.00000000E-99   .17974121E+05   .32789192E+04
.60859443E+01   .37327468E+03   .38998800E+03
578.60184E-00     1
548.63920E-00     2
541.30423E-00     3
540.13546E-00     4
540.01322E-00     5
540.00306E-00     6
540.00055E-00     7
540.00003E-00     8
  .
  .
  .
```

b. Temperature versus Time for Layers of Flat Plate

```
 THETA=           Y=                RET=
.40000000E+01   .20000000E+01   .22500000E+08

 TMELT=           OFFF=             EMISSIVITY=
.28050000E+04   .30000000E+04   .80000000E-00

 MATERIAL -- DTIME, M, K, RHO, CP, TAUT, NLAY
274.09802E-04      1
.13470000E-01   .11490000E+03   .69680000E-00   .80000000E-02
300.54519E-04      2
.17470000E-01   .63680000E+03   .63400000E-01   .51000000E-02

 DTIME=           DTOUT=            TLO=          THI=
.25000000E-01   .50000000E-00   .16000000E+02   .18000000E+02


 **- FOR EACH OUTPUT TIME STEP ---
 TIME        ALT,KFT     VEL,FT/SEC       RE
 QW          QDOT        H       TAUAB --- HEAT COEFFS
 MACH NO.    PRESSURE    TEMPERATURE -- LOCAL
 MACH NO.    PRESSURE    TEMPERATURE -- FREE STREAM
 TEMPERATURE AND COUNT FOR EACH SKIN LAYER

  1
.16000000E+02   .45981030E+02   .62311290E+04   .21965317E+08
.55978512E+01   .55945795E+01   .22409938E-02   .00000000E-99
.60763760E+01   .42585199E+03   .43257847E+03
.64375182E+01   .29491558E+03   .38998800E+03
540.00000E-00      1
540.00000E-00      2
540.00000E-00      3
540.00000E-00      4
540.00000E-00      5
  2
.16025000E+02   .45438510E+02   .61936070E+04   .22369129E+08
.55888277E+01   .55855560E+01   .22638823E-02   .00000000E-99
.60422289E+01   .43564050E+03   .43220779E+03
.63987534E+01   .30269147E+03   .38998800E+03
540.18782E-00      1
540.18782E-00      2
540.00000E-00      3
540.00000E-00      4
540.00000E-00      5
  3
.16050000E+02   .44895190E+02   .61560130E+04   .22779691E+08
.52755893E+02   .52752617E+02   .20566093E-01   .00000000E-99
.60079820E+01   .44566301E+03   .43183789E+03
.63599142E+01   .31068475E+03   .38998800E+03
541.94009E-00      1
541.94009E-00      2
540.01234E-00      3
540.00000E-00      4
540.00000E-00      5
```

```
 4
.16075000E+02  .44351110E+02  .61183460E+04  .23197024E+08
.53101702E+02  .53098384E+02  .20967106E-01  .00000000E-99
.59736339E+01  .45592409E+03  .43146868E+03
.63209992E+01  .31890116E+03  .38998800E+03
543.50357E-00   1
543.50357E-00   2
540.13822E-00   3
540.00081E-00   4
540.00000E-00   5
 5
.16100000E+02  .43806250E+02  .60806070E+04  .23621220E+08
.53450131E+02  .53446774E+02  .21377028E-01  .00000000E-99
.59391860E+01  .46642978E+03  .43110022E+03
.62820190E+01  .32724754E+03  .38998800E+03
544.91317E-00   1
544.91317E-00   2
540.35036E-00   3
540.00978E-00   4
540.00010E-00   5
 21
.16500000E+02  .34981100E+02  .54669450E+04  .30878029E+08
.58520691E+02  .58516958E+02  .29102045E-01  .00000000E-99
.53470380E+01  .67381401E+03  .42943836E+03
.56181347E+01  .49802911E+03  .39414844E+03
558.74673E-00   1
558.74673E-00   2
547.05337E-00   3
542.20022E-00   4
541.00556E-00   5
 41
.17000000E+02  .23658990E+02  .46737680E+04  .35624770E+08
.59766647E+02  .59762619E+02  .40451952E-01  .00000000E-99
.43973177E+01  .10433726E+04  .46309880E+03
.45750279E+01  .83142794E+03  .43441169E+03
569.27854E-00   1
569.27854E-00   2
555.62899E-00   3
548.13966E-00   4
545.80388E-00   5
 61
.17500000E+02  .12002670E+02  .38514940E+04  .38927373E+08
.53192654E+02  .53188417E+02  .52959705E-01  .00000000E-99
.34908104E+01  .15773304E+04  .49793592E+03
.36020070E+01  .13446030E+04  .47590309E+03
576.32355E-00   1
576.32355E-00   2
563.16318E-00   3
555.14646E-00   4
552.48327E-00   5
 81
.18000000E+02  .40000000E-04  .30000180E+04  .39679877E+08
.39067380E+02  .39063042E+02  .64110878E-01  .00000000E-99
.26212649E+01  .23419992E+04  .53411950E+03
.26874980E+01  .21162109E+04  .51868786E+03
579.56281E-00   1
579.56281E-00   2
568.94551E-00   3
561.82591E-00   4
559.34920E-00   5
```

c. Temperature versus Time for Layers of Cone

```
 THETA=              Y=                  RET=
.40000000E+01   .20000000E+01   .22500000E+08

 TMELT=              QEFF=               EMISSIVITY=
.28050000E+04   .30000000E+04   .80000000E-00

 MATERIAL -- DTIME, M, K, RHO, CP, TAUT, NLAY
274.09802E-04      1
.13470000E-01   .11490000E+03   .69680000E-00   .80000000E-02      1
300.54519E-04      2
.17470000E-01   .63680000E+03   .63400000E-01   .51000000E-02      3

 DTIME=              DTOUT=              TLO=            THI=
.25000000E-01   .50000000E-00   .16000000E+02   .18000000E+02

 MACH NO.  PRESSURE   TEMPERATURE -- LOCAL
.60763760E+01   .42585200E+03   .43257850E+03

 **- FOR EACH OUTPUT TIME STEP ---
 TIME        ALT,KFT     VEL,FT/SEC       RE
 QW          QDOT         H       TAUAR --- HEAT COFFFS
 TEMPERATURE AND COUNT FOR EACH SKIN LAYER

  1
.16000000E+02   .45980000E+02   .62310000E+04   .21965315E+08
.96957630E+01   .9692 713E+01   .38815149E-02   .00000000E-99
540.00000E-00      1
540.00000E-00      2
540.00000E-00      3
540.00000E-00      4
540.00000E-00      5
  2
.16025000E+02   .45980000E+02   .62310000E+04   .21965315E+08
.96957630E+01   .96924913E+01   .38815149E-02   .00000000E-99
540.32592E-00      1
540.32592E-00      2
540.00000E-00      3
540.00000E-00      4
540.00000E-00      5
  3
.16050000E+02   .45980000E+02   .62310000E+04   .21965315E+08
.96939141E+01   .96906345E+01   .38813655E-02   .00000000E-99
540.61424E-00      1
540.61424E-00      2
540.02141E-00      3
  .
  .
  .
  .
 81
.18000000E+02   .45980000E+02   .62310000E+04   .21965315E+08
.96539314E+01   . 6504773E+01   .38781258E-02   .00000000E-99
.00000000E-99   .00000000E-99   .00000000E-99   .24000000E-00
.11128778E+04   .64762286E-06   .77095465E-05   .24731995E-00
547.43653E-00      1
547.43653E-00      2
  5.14782E-00      3
543.78103E-00      4
543.32626E-00      5
```

Appendix B

1959 ATMOSPHERIC PROPERTIES

Table I presents 1959 atmospheric properties used as input to the Fortran program.

Table I. ARDC 1959 Atmospheric Properties

ALT, Meters	T, °K	P, Newtons/m²	Card #
0.0	288.16	101325.	1
11000.	216.66	22632.	2
25000.	216.66	2488.6	3
47000.	282.66	120.444	4
53000.	282.66	58.3215	5
79000.	165.66	1.00946	6
90000.	165.66	.104438	7
105000.	225.66	.00745265	8
160000.	1325.66	.362003 E-03	9
170000.	1425.66	.282362 E-03	10
700000.	3325.66	0.0	11

The following changes in dimensions are made, and the properties are stored into memory as:

$$AP\ (K,\ 1) = ALT_{ft} = ALT_{meters} \times 3.2808333 \qquad \text{(B-1)}$$

$$AP\ (K,\ 2) = T,\ ^\circ R = T,\ ^\circ K \times 1.8 \qquad \text{(B-2)}$$

$$AP\ (K,\ 3) = P,\ lbs/ft^2 = P,\ Newtons/m^2 \times .0208854 \qquad \text{(B-3)}$$

where K = 1 to 11

The local velocity, V_∞, is given in ft/sec and the local altitude, ALT, is given in kilo-feet (geometric measure) and is converted to feet (geopotential measure).

$$ALTF = 20856000.\ (ALT)\ /\ (20856.\ +\ ALT) \qquad \text{(B-4)}$$

$$\Delta ALT = DALT = ALTF - AP_{K,1} \qquad \text{(B-5)}$$

$$T_\infty = AP_{K,2} + ALT\ (TS) \qquad \text{(B-6)}$$

where TS is the temperature slope for the atmosphere layer.

$$TS = \frac{\Delta\ AP\ \text{Temperature}}{\Delta\ AP\ \text{Altitude}} \qquad \text{(B-7)}$$

When TS = 0.0

$$P_\infty = AP_{K,3} / e^{j} \qquad \text{(B-8)}$$

where

$$e = 2.718281828 \qquad \text{(B-9)}$$

and

$$j = .01879\ \Delta ALT / AP_{K,2} \qquad \text{(B-10)}$$

When TS $\neq$ 0.0

$$P_\infty = AP_{K,3} \left[\frac{AP_{K,2}}{T_\infty}\right]^{j} \qquad \text{(B-11)}$$

where

$$j = .01879/TS \qquad \text{(B-12)}$$

Then

$$\rho_\infty = .01879\ P_\infty / T_\infty \qquad \text{(B-13)}$$

and

$$M_\infty = V_\infty / \sqrt{\gamma R_g\ T_\infty} \qquad \text{(B-14)}$$

SYMBOLS

TBODY		Type of configuration - 1. Sphere 2. Flat plate 3. cone
NCFIT		Number of curves fitted for input data
TH	θ	Angle, deg: Sphere; position angle Flat plate or cone; used for identification
	D	Nose diameter of sphere, ft
RN	R_n	Nose radius of sphere, ft
Y	Y	Length along surface, ft
RNORY		Input symbol (RN or Y)
QR	q/q	Ratio of laminar heat transfer to stagnation rate heat transfer, from Figure 5
RET	Re_t	Transition Reynolds number, given for FP or cone
RE	Re	Local Reynolds number, defined by Equation (36) for FP or cone
QRRET		Input symbol (QR or RET)
TMELT		Melting temperature for wall, °R
QE	q_{eff}	Effective heat of ablation, Btu/lb
E	ϵ	Emissivity of wall material
NMAT		Total number of materials; 1, 2 or 3
C(M)	k_m	Material thermal conductivity, Btu/ft-sec - °R
RHO(M)	ρ_m	Material density, lbs/ft^3
CP(M)	C_{P_m}	Specific heat for the material, Btu/lb - °R

TAUT	τ_{tot}	Total thickness of the material, ft
TAU(M)	τ_m	Thickness of each layer of the material, ft
NL1-2-3	$NLAY_m$	Number of layers of each material (Total cannot exceed 14)
F, B	F_m, B_m	Functions of material properties, defined by Equations (39) to (41)
TIME	t	Local time, sec
DTIME	Δt	Time increment, sec, used for calculations, Equation (38)
DTOUT		Time increment, sec, used for output; Multiple of DTIME
TLO	t_{lo}	Initial time, sec, TLO $\geqq$ 0.0
THI	t_{hi}	Upper time limit, sec
NT		Total number of time steps, Equation (A-1)
T1620		Estimate of 1620 machine time required, Equation (A-11)
TPRNT		Count for time print-out
ABOUT		Test for output of TIME, ALT, and VEL at first ablation
NUM_i	NSEG	Number of segments to each of 2 or 5 curves given (Total number of segments cannot exceed 15)
$CON_{1,2}$	X_{lo}, X_{hi}	Limits of curve segment, input data
CON_3, 4, 5, 6	A_o, 1, 2, 3	Normalized cubic curve fit constants, used in Equation (A-4)
TEMP	T	Temperature for each skin layer at each time step, °R; given for initial time step, then defined by Equations (49) to (55)

TEMPL	T'	Temperature for each layer at previous time steps
DTEMP	ΔT	Temperature increment for the local layer, Equation (42)
TW	T_w	Wall temperature, °R, defined by Equations (49) and (53)
TEMP(NL)	T_{NL}	Temperature for innermost point, defined by Equations (52) and (55)
D1-2-3	$D_{1, 2, 3}$	Incremental temperature distribution, defined by Equations (43) to (45)
FM	M_∞	Free stream Mach number, Equation (B-14)
SM	M_s	Local Mach number Sphere: from Equation (25) FP or Cone: given constant or $f(M_\infty)$, Equation (A-8)
PF	P_∞	Free stream pressure, lbs/ft^2, Equations (B-8) and (B-11)
PS	P_s	Local pressure, lbs/ft^2 Sphere: from Equation (23) FP or Cone: given constant or $f(M_\infty)$, Equation (A-9)
PSVPT	P_s/P_{tot}	Ratio of local pressure to stagnation pressure, Equation (24)
TF	T_∞	Free stream temperature, °R, Equation (B-6)
TS	T_s	Local temperature, °R Sphere: from Equation (27) FP or Cone: given constant or $f(M_\infty)$, Equation (A-10)
AP		Atmospheric Properties of Table I in Appendix B
$AP_{K,1}$		Altitude, ft, geopotential measure, Equation (B-1)

$AP_{K,2}$		Atmospheric temperature, °R, Equation (B-2)
$AP_{K,3}$		Atmospheric pressure, lbs/ft^2, Equation (B-3)
ALT	ALT	Local altitude, kilo-feet, geometric measure, Equation (A-6)
ALTF		Local altitude, ft, geopotential measure, Equation (B-4)
DALT	Δ ALT	Difference between local and layer base altitude, ft, geopotential measure, Equation (B-5)
VEL	V_∞	Local free stream velocity, ft/sec Equation (A-7)
DF	ρ_∞	Free stream density, lbs/ft^3, Equation (B-13)
	ρ sea level	Sea level density, 0.002378 slugs/ft^3
QAB	q_{ab}	Heating rate during ablation, Equation (A-12)
TAUAB	τ_{ab}	Preliminary estimate of total ablation thickness, in., Equation (A-13)
QW	q_w	Aerodynamic heating rate, Btu/ft^2 - sec Equations (28) and (47)
QDOT	$\dot{q}$	Defined by Equation (48)
TREC	T_{rec}	Recovery temperature, °R, Equation (46)
H	H	Aerodynamic heat coefficient, Btu/ft^2-sec-°R, defined by Equations (15), (19), (29), (32), and (35)
Z1-2-3	$Z_{1,2,3}$	Factors of Equations (7), (15) and (19). Defined by Equations (8) to (10) and (20) to (22)
HX		Flat plate to cone heat transfer factor, as used in Equations (32) and (35)
	h	Enthalpy, ft^2/sec^2, used in Equation (28)

CREF	k^*	Reference thermal conductivity, Btu/ft-sec-°R Equations (12a) and (12b)
UREF	μ^*	Reference viscosity, lbs-sec/ft^2, Equation (13)
PRREF	$P_r{}^*$	Reference Prandtl number, Equation (14)
TREF	T^*	Reference temperature, °R, Equation (11)
COP	C_p	Specific heat for air, Equation (56)
G	γ	Ratio of specific heats; for air, $\gamma = 1.4$
GL	γ_s	Computed γ as a function of temperature, Equation (57)
R	R	Recovery factor: laminar, $R = 0.85$, turbulent, $R = 0.892$
GA	g_a	Acceleration for gravity; 32.174 ft/sec^2
RG	R_g	Gas constant, for air, $R_g = 1716$ ft^2/sec^2 - °R
	σ	Stefan-Boltzmann constant, $0.48096 \times 10^{-5} \dfrac{\text{Btu}}{\text{ft}^2\text{-sec-°R}^4}$
	St	Stanton number, Equations (1) and (17)
	Nu	Nusselt number
	C_f	Skin friction coefficient, Equations (3) and (18)
	f_1, f_2	Leading edge C_f proportionality factor for laminar and turbulent boundaries
	β	Velocity gradient parameter

SUBSCRIPTS

AB	Ablation properties
∞	Free stream properties
S	Local properties
M	Material properties, counts materials from 1 to NMAT
NL	Total number of skin layers plus end point, NL $\leqq$ 15
L	Number of the layer, from 1 to NL
N	Counts time steps
I	Counts curves fitted for input data, from 1 to NCFIT
inc	Incompressible conditions
o	Stagnation conditions
TOT	Total conditions
K	Number of base of altitude layer
FP	Flat plate
W	Wall

SUPERSCRIPTS

*	Reference properties
'	Temperatures at previous time step

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13. ABSTRACT

The equations and a Fortran program to calculate supersonic and hypersonic aerodynamic heat transfer rates and transient temperature distributions for spherical leading edges and flat plate surfaces are presented in this report. The missile skin is composed of one to three different slab materials and/or thin wall combinations for flight trajectories or wind tunnel conditions. The Fortran program is written for the IBM 1620 40K digital computer.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Stagnation regions						
Flat plate regions						
One dimensional temperature distribution						
Specific heat ratios						
Flight environment						
Fortran						

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